Renewable and Sustainable Energy Reviews 16 (2012) 1745–1753

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energy and environmental balance of biogas for dual-fuel mobile applications

S. Lacour[a,*], T. Chinese[a], D. Alkadee[b], C. Perilhon[b], G. Descombes[b]

[a] Laboratoire de genie des procedes pour l'environnement, l'energie et la sante (LGP2ES-EA21), Irstea, 1 Rue Pierre-Gilles de Genne, CS 10030, F-92761 Antony cedex, France
[b] Laboratoire de genie des procedes pour l'environnement, l'energie et la sante (LGP2ES-EA21), case 333, 292 rue Saint-Martin, 75141 Paris, France

ARTICLE INFO

Article history:
Received 26 August 2011
Received in revised form
18 November 2011
Accepted 25 November 2011
Available online 18 January 2012

Keywords:
Biogas
Biofuel
LCA
Energy balance
Carbon balance
Agriculturalwaste treatment
Energy production

ABSTRACT

Considerable research is currently being devoted to seeking alternative fuels to comply with transportation needs while reducing the environmental impact of this sector. Within the transport activity sector, on road vehicles and agricultural machinery require around 2 Mtoe energy in France. The anaerobic digestion of farm waste could roughly cover these needs. This paper aims to study the environmental and energy interest of this short power supply path. An ideal biogas production system has been built up from the average characteristics of current rural biogas plants in France. Pollutant emissions, energy demands and production are assessed for various scenarios in order to produce methane for dual fuel engines. Life cycle assessment (LCA) is used to evaluate the environmental impact of dual fuel agricultural machines, compared to diesel engines. The energy balance is always in disfavour of biogas fuel, whereas LCA energy indicators indicate a benefit for biogas production. This gap is related to the way in which the input of biomass energy is handled: in conventional biofuel LCA, this energy is not taken into account. A carbon balance is then presented to discuss the impact of biogas on climate change. Dual fuel engines were found to be interesting for their small impact. We also show, however, how the biogenic carbon assumption and the choice of allocation for the avoided methane emissions of anaerobic digestion are crucial in quantifying CO_2 savings. Other environmental issues of biogas fuel were examined. Results indicate that are management and green electricity are the key points for a sustainable biogas fuel. It is concluded that biofuel environmental damage is reduced if energy needs during biofuel production are covered by the production process itself. As agricultural equipment is used during the biofuel production process, this implies that a high substitution rate should be used for this equipment.

Contents

* Corresponding author at: Laboratoire de genie des procedes pour l'environnement, l'energie et la sante (LGP2ES-EA21), Irstea, 1 Rue Pierre-Gilles de Genne, CS 10030, F-92761 Antony cedex, France. +33 1 40 96 62 89; fax: +33 1 40 96 61 62.
E-mail address: stephanie.lacour@irstea.fr (S. Lacour).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2011.11.029

Nomenclature

LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
FFD	Fossil fuel depletion (Pt)
CED	Cumulative energy demand (Pt)
η	energy efficiency (%)
COP	Coefficient of performance
RDAIS	Respiratory diseases related to inorganic species
$M_{C/OC}$	Mass ratio of carbon per organic matter content
$M_{H/OC}$	Mass ratio of hydrogen per organic matter content
PM	Particulate matter (g/m^3)
NMVOC	Non-methane volatile organic compounds g_C/m^3
LHV	Low heating value (MJ/kg$_{fuel}$)
GHG	Greenhouse gases (equivalent ton of CO_2)

1. Introduction

In view of the depletion of fossil fuel resources, considerable research is being devoted to looking for alternative fuels to comply with transportation needs while reducing the environmental impact of the transport activity sector. In this sector, off road vehicles and agricultural machinery consume a small, but vital amount of energy of around 2 Mtoe in France [1]. As for transport, the European goal is to reduce both their fuel consumption and their greenhouse gas emissions by 20% in 2020 and the target is even to reduce these by a factor of 4 in 2050. Given the thermodynamic principle of diesel engines and the Carnot limit, such a decrease can only be achieved with fuel changes.

Among biofuels, biogas is an interesting candidate because it can easily be used to partially replace diesel fuel in the compression ignition engines generally used for tractors. Biogas also comes from the methanisation of farm waste. This process is however poorly developed in France, with existing stations producing only 150 toe, but the French biogas potential is much higher and could cover roughly half of the energy needs if tractors were equipped with dual fuel engines [2].

Anaerobic digestion is one way to produce energy from biomass. Biomass is an ambiguous word in energy production. It refers both to the production of biofuel and to the generation of electricity by firing and co-firing. The gasification of biomass is studied for both fuel and electricity applications [3]. The most common way to use the biogas produced by anaerobic digestion is currently to produce electricity and heat. The electricity is sold whereas the heat is often used for urban heating plants, when it is produced from agricultural and municipal organic matter [4]. Sometimes, biogas is purified and injected into the gas network for use. When biogas is used for transport applications, it is then called *biofuel* in accordance with the directive 2009/28/EC European directive. Anaerobic digestion may also be regarded as a waste management system that provides organic material for soils [5]. This point is very important when dealing with agricultural waste digestion. Due to these heterogeneous applications, the environmental and energy interest of biogas is somewhat difficult to evaluate, although it is in general positive compared to fossil energy.

A certain number of studies have already been carried out to qualify the environmental impact of anaerobic digestion, using the conventional method of life cycle assessment, such as [6] or [7]. These papers compare life cycle assessment for different uses of the biogas produced on a specific site. The results generally conclude that the use of biogas as biofuel is interesting for climate change, acidification and eutrophisation. Borjesson and Berglund [5] also discussed the environmental impact of various biogas production systems in Sweden and showed the importance of methane losses in these systems. Their inventories give an idea of the scattering of emission among various methanisation processes. They also demonstrate the sensitivity of climate change impact to methane losses during methanisation. This work was extended to an energy performance analysis of systems in [8]. The energy content of the methanisation process was discussed for different scenarios and an energy performance indicator established for each production system. As the main focus was on the methanisation system, the end-use of biogas was not included in the analysis. This is however very relevant in our case since many emissions are linked to the purification of the gas, which is required for the biogas fuel application. Borjesson's approach differs from that of Moras [9], in which different kinds of valorisation were studied for the same biogas production system. In [9], cogeneration with biogas was compared to heat and power generation by fossil fuels and results showed the great attractiveness of biogas in reducing the global warming potential. Moras proposed an LCA of cogeneration with biogas that included effluent management at the farm level, showing that methanisation is not only a way to produce energy: for farm waste, it is also often a way to reduce the global warming impact of farms by reducing their fugitive methane emissions.

All the studies published in the literature focus on the valorisation of biogas rather than on its interest as biofuel. In this paper, we aim to present the environmental assessment of biogas as biofuel. The biogas is produced from agricultural waste and used by agricultural machines, leading to a short power supply path. An emission inventory was therefore carried out on a typical farm digester producing biogas. A purification stage was added in order to produce high quality methane that can be used in current diesel engines. Different scenarios were considered to study the environmental impact of biogas fuel compared to that of diesel fuel. The results are first discussed from the energy point of view. The energy efficiency is computed for each scenario and compared to LCA energy indicators. It is shown how environmental and energy optimisation may diverge. The following section focuses on the climate change impact of biogas fuel. The carbon balance is used to explain the main parameters governing the assessment of climate change impact. Lastly, a global environmental assessment is presented through the endpoint method "Ecoindicator 99". The impact of biogas fuel on the respiratory diseases due to inorganic species is demonstrated.

2. Emission inventory of a rural waste treatment plant

2.1. Goal, boundary system and allocation choice

The most common method for environmental assessment is life cycle assessment. Our assessment aims to study the environmental impact of biogas/fuel for mobile applications, focusing on "biogas as biofuel": the goal is to produce results that could

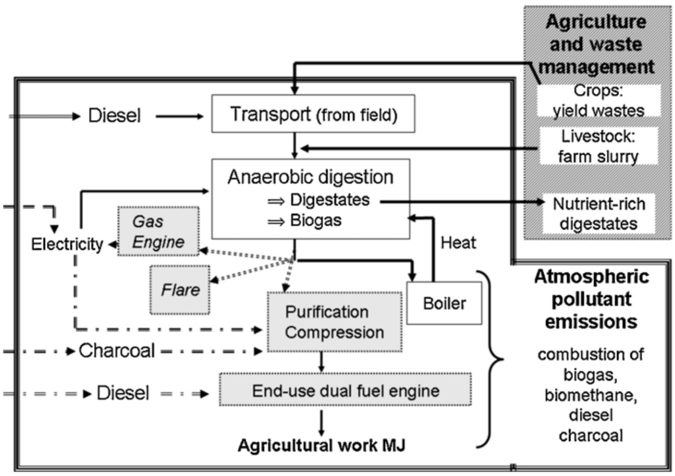

Fig. 1. Functional scheme of the biogas plant and corresponding LCA area: grey boxes and dotted lines represent respectively processes and quantities that vary according to the production scenario.

be compared to fossil fuels or other biofuels. We have therefore drawn on the method detailed in [10] to apply some choices specifically related to the comparative assessment of transport fuels. The first step in LCA consists in doing the pollutant emission inventory (life cycle inventory, LCI [11]). This inventory was carried out on a typical rural digester producing biogas. First, however, the system boundaries have to be considered and defined.

The purpose of anaerobic digestion is to manage waste and/or to produce energy. In France, agriculture is responsible for 76% of N_2O emissions through soil nutrition and organic spreading. About 73% of French methane emissions come from livestock [1]. During the storage of slurry and manure, methane emissions are released. Storing these wastes in a digester avoids some of these methane emissions. Manure digestion is also a way to decrease landfill emissions and pollutant emissions during spreading, since N_2O emissions decrease with digested manure, which also improves the ammonium uptake in soils by 10%. The balance between NH_3, CH_4 and N_2O emissions through digestion is therefore very relevant for the analysis of agricultural systems: by improving waste management, waste digestion is a good means to reduce the substantial contribution of agricultural practices. Due to the strategic weight of these balances for agriculture, biogas is here considered as the coproduct of an *improved waste treatment*. As the focus here is on biogas, the secondary coproduct of digestion, we did not take into account the part of waste management represented by spreading manure (Fig. 1). Therefore, only emissions coming from biogas and its combustion are taken into account. This choice is of course very severe for the fuel and this assumption plays a key role in the greenhouse gas (GHG) balance of biogas. That is why we also present some scenarios that take into account the amount of methane emissions avoided by enclosed digester storage. In this case, 100% of the avoided methane was allocated to biogas, as this makes it straightforward to demonstrate the weight of this allocation rate on the results.

The whole perimeter of our system is described in Fig. 1: it excludes the spreading operation of digestates, symbolised in the right box about waste management, but includes all biogas combustions. Dotted lines and gray boxes are used for the variable parameters in our simulations. The following additional hypotheses were made: as farm waste is mainly made of livestock wastes, it has the same composition as traditional slurry. The construction and maintenance of the digester is not taken into account, as recommended by Poitrat [10] for comparative LCA of biofuels. The construction and maintenance of a dual fuel engine is similar to that of a diesel engine. Our energy production starts from agricultural waste transport to the digester. All the pollutant emissions during digestion and biogas treatment are related to the fuel production system.

The biogas production plant simulated in this paper is an ideal model of a methanisation unit: its characteristics were defined by analysing existing agricultural waste treatment plants in France and selecting the average characteristics in order to build a "mean plant". However, as we also wish to assess the environmental interest of biomethane for agricultural machinery, it was necessary to add a purification stage that could guarantee high quality methane for dual fuel engines.

2.2. Functional unit

For transportation fuels, in a cradle-to-grave analysis, the grave of the duty cycle is the engine in which combustion takes place. As passenger cars make the major contribution to energy consumption, the conventional functional unit is generally given in kilometers (veh.km or kilometers travelled). A typical value of fuel consumption is about 1.70 MJ/km for a standard Euro5 diesel car [12]. This corresponds to an hourly fuel consumption of 2.83 l/h when driving at 60 km/h. The present study, however, concerns biofuels used in tractors. The functional unit is therefore related to agricultural work. In pollutant inventories [13], non mobile road engine activity is described by the period of duty per year D_{year}. The tractor is described by its mechanical engine power P_{trac}. The typical unit for agricultural machines is then given by MJ of agricultural work E_{tract}:

$$E_{tract} = P_{trac} \times D_{year} \times C_{load} \tag{1}$$

E_{tract} expresses the quantity of mechanical energy needed for agricultural operation, i.e. the equivalent of km for cars. The engine load coefficient, C_{load}, is generally around 0.55–0.6. This means that a tractor uses a high percentage of its nominal power, unlike cars. Its energy consumption is therefore around 3.06 MJ of fuel per MJ of agricultural work, i.e. around 20.2 l/h for a typical tractor delivering 110 kW at power-take-off.

2.3. Process description

Biogas production comprises four different steps: waste collection, digestion, gas purification, and use. The digester is a typical small rural digester whose characteristics were derived from existing digesters in France. The methanisation unit valorises 4150 tons of organic waste and manure per year. As 80% of this substrate comes from the farm (livestock waste) where the digestor is installed, its transport does not cause emissions. Contrarily, the remaining 20% comes from a neighbourhood with a 10 km mean radius and it is collected with a diesel tractor with an average fuel consumption of 60 l/100 km [14]. The average transport distance needed to supply 20% of the substrate was estimated to be about 5 km/day.

The substrate contains 15% of dry matter (DM), around 62% of which is organic content (OC). As we are interested in the energy balance of biogas fuel, it is necessary to introduce the energy content of the agricultural waste because it is part of the energy input in our system. The energy content in waste was assessed following Kalinci [15] from the carbon and hydrogen contents. The generic organic composition is given by the formula $C_{100}H_{200}O_{100}N_{15}$ and is used to assess the carbon and hydrogen ratio in the organic content of waste. Given the low heating values (LHV) of carbon (32.7 MJ/kg) and of hydrogen (120 MJ/kg), the potential energy within the waste

Table 1
Chemical composition of biogas (volume) produced by rural waste digestion.

Chemical	Amount (%)	Chemical	Amount (%)
CH_4	65%	H_2O	6% (40 °C)
CO_2	26%	H_2S	6300 ppm (2.67%)
N_2	0.5%	NH_3	75 mg/m^3 (0.03%)
O_2	0.3%		

can then be assessed as follows [16]:

$$E_{waste} = \mathrm{LHV_{OC}} \times M_{\mathrm{OC}} = (M_{\mathrm{C/OC}} \times \mathrm{LHV_C} + M_{\mathrm{H/OC}} \times \mathrm{LHV_{H_2}}) \times M_{\mathrm{OC}} \quad (2)$$

The mass of carbon and hydrogen in waste, multiplied by their respective low heating values then gives an idea of the energy content of the waste. This energy is part of the primary energy entering the system. By taking this energy amount into account, we are able to deal with biomass both as a waste (ton of waste) and as an energy. We will see later in the paper the interest of taking the energy content of waste into account.

2.3.1. Anaerobic digester

The biogas production station analysed in this paper is based on a continuously stirred biological methanisation process taking place thanks to mesophilic anaerobic microorganisms working at 40 °C. The collected waste are introduced in a 35 m^3 storage vessel, stirred and then pumped into the main reactor. The main reactor has a volume of about 120 m^3, it is thermally insulated, heated to a temperature of 40 °C and equipped with a stirring system so as to obtain the ideal conditions for the onset of methanisation. The substrate is then pumped into a second 340 m^3 storage vessel where the methanisation process terminates; this second reactor is also equipped with a stirring system. The biogas produced in the main reactor and the second storage vessel is then pumped out.

The net production of methane is about 116 tons per year. 9% of the production is sent to a boiler and burnt to heat the main reactor. 10% is burnt in a flare and its energy is lost: a flare is generally used to manage seasonal variations in the biogas flow. The flare also burns during maintenance operations. Biogas losses also occur during the production process. Following [5], these losses are assumed to be 2% of the raw gas production. Overall, the digester is considered to avoid the release of 14.5 kg of CH_4 per ton of waste, that would otherwise be produced if slurry was stored in a open tank [17]. The rest of the biogas is sent to the purification unit for the valorisation of the biogas as biofuel. Its average biogas composition is given in Table 1.

2.3.2. Purifying the fuel

Formerly, biogas could be directly used in tractor engines, but its content in sulphur and ammonia is too high to comply with current fuel directives. New fuels for mobile applications should have a low sulphur content, below 500 ppm for low sulphur diesel and even under 15 ppm for ultra-low-sulphur fuels. This low content is necessary to achieve low particle emissions. Purification also allows to work with a fuel having a high specific energy by eliminating the CO_2 fraction and keeping a quite pure methane. This point is particularly important for mobile applications where the mass of fuel carried has to ensure a long working capacity.

The purification process comprises four stages: (1) filtration by a biological filter containing sulphur bacteria, (2) elimination of water vapour by a thermal process, (3) filtration by activated charcoal to remove traces of ammonia and hydrogen sulphide, and (4) elimination of carbon dioxide by a pressure swing adsorption process.

The inputs of the purification step are linked to electricity and charcoal consumption. When the charcoal is saturated, most of the existing digestion plants usually burn it. This causes non-negligible environmental consequences that have been taken into account in our inventory.

The total electrical consumption of the digestion unit, including stirring and pumping of the substrate and the electrical needs for compression of the gas, was estimated to be about 1 kWh per m^3 of raw biogas produced. The related emissions depend on the origin of the electricity. External electricity emissions are taken from the Ecoinvent database. For "Local elec", a dual fuel engine is used to produce electricity and it has the same emission characteristics as those of tractors (see below): the conversion from mechanical to electrical energy has an efficiency of 0.9.

2.3.3. Burning in dual fuel engines

Dual fuel engines are diesel engines working with a mix of diesel and gas. The gaseous fuel is mixed with air in the admission step. The mixed gas is then injected into the cylinder and fired by injection of a pilot quantity of diesel at the end of the compression stage. The efficiency of the dual fuel engine as well as its environmental impact strongly depend on the tuning strategy used.

We assume that the dual fuel engine works with a constant diesel flow whereas the power fluctuates with the methane flow. The nominal power of the tractor engine is about 110 kW, an average value for agricultural engines. Methane consumption and the substitution ratio are computed from the efficiency values for each of the 6 test cycle modes from the OECD code used for tractor performance (Table 2). For high loads, dual fuel efficiency is generally higher than diesel efficiency. In the low load range, the efficiency is generally lower due to difficulties in controlling gas combustion: due to the higher octane number of methane, it burns more slowly than diesel. The dual fuel engine runs with a constant diesel mass injection of 1.24 g/s. Methane flow is adapted to engine load to yield the power needed. The efficiency values for this kind of dual fuel engine are taken from [18]. These assumptions lead to an average efficiency of 23.3% for the dual fuel engine, versus 22.6% for diesel. The energy substitution rate is around 83% of diesel replaced by methane. Concerning pollutant emissions, Ref. [19] indicated that a well optimised dual fuel engine has the same emission levels as a diesel engine. We therefore considered that both diesel and dual fuel engines respected the emission standard of the Tier 3b regulation, currently applied to tractors.

2.4. Global emission inventory

All the pollutant emissions during the biogas/biofuel production and its use are summarised in Table 3. Emissions associated with the production process are given per year. However, the amount of energy available for use is not constant in our analysis and it varies according to different scenario that are described hereafter. The emissions during use in Table 3 refers to the reference scenario. The methanisation station, in the reference scenario, produces 116 tons of methane per year. In this step, the life cycle inventory was carried out and emission data were collected for the production system studied here which produces methane for non road mobile machines. Input flows and output flows were defined for our biogas plant and entered in the Simapro software in order to begin the life cycle impact assessment.

3. Impact assessment of biogas fuel production

3.1. Simulation scenario

The life cycle impact assessment phase (LCIA) is the third phase of the LCA; its purpose is to provide additional information to better understand the environmental significance of the process. LCIA is based on computations and data from the Simapro software. From

Table 2
Engine use and efficiency of dual fuel and diesel engines.

OECD parameters			Dual fuel			Diesel	
Time weight ratio	Engine speed ratio	Load ratio	Engine efficiency ratio	Diesel consumption (kg/s)	Biogas consumption (kg/s)	Engine efficiency ratio	Diesel consumption (kg/s)
0.167	0.6	0.6	2.35E−1	1.24E−3	4.56E−3	2.33E−1	6.62E−3
0.167	0.6	0.4	1.75E−1	1.24E−3	3.97E−3	1.90E−1	5.41E−3
0.167	0.9	0.4	1.75E−1	1.24E−3	3.97E−3	1.90E−1	5.41E−3
0.167	0.9	0.8	2.65E−1	1.24E−3	5.58E−3	2.40E−1	8.57E−3
0.167	0.9	0.8	2.65E−1	1.24E−3	5.58E−3	2.40E−1	8.57E−3
0.167	1.0	1.0	2.85E−1	1.24E−3	6.66E−3	2.65E−1	9.70E−3

the first simulations, LCIA results show that electricity use in the production process plays an important role in the environmental assessment of the results. The flare also has a great impact on the energy efficiency of the process. Lastly, the allocation of avoided methane emissions greatly influences the results. The weights of all these factors are illustrated using different scenarios for biogas production. The main characteristics of these scenarios are detailed below:

1. "Biogas ref": this scenario is our reference scenario. It is based on the data described in the inventory section. This scenario is built using the physical pollutant emissions: the biogenic nature of carbon dioxide in biogas is not taken into account, although it could be set to zero (Directive2009/28/EC). We did not take avoided methane emissions into account. French electricity emissions are taken from the Ecoinvent99 database.
2. "French elec": this scenario is identical to the biogas ref scenario except that here we take avoided emissions of methane into account. These avoided emissions are allocated 100% to biogas production. This assumption is made in order to show the range of the avoided emissions of methane. Our purpose is not, however, to discuss the way in which these emissions are allocated between agricultural practices for waste and energy production. The influence of avoided methane emissions is shown by comparing this scenario with "Biogas ref".
3. "Local elec": in this scenario, part of the biogas production is used to produce the electricity needed for the digester and gas purification/compression. The amount of gas used for electricity production is computed from the LHV of the raw biogas, assuming that the electric generator efficiency is 30%. Pollutant emissions are given as a proportion of gas consumption, with the same chemical composition as for the boiler. It should be noted that for this scenario, the energy available for use is reduced.
4. "Without Flare": the methane is stored in gas tanks after purification. We assumed that this storage facilitates the management of production fluctuations by providing intermediate storage capacities (during heat treatment, purification...). We therefore assume, in this scenario, that it is possible to eliminate the flare and recover the entire gas production for use.
5. "Diesel": this scenario corresponds to the case where the tractor is used with conventional diesel fuel (the most common fuel for tractors in Europe). We mainly used the data of the Ecoinvent database for the diesel fuel currently sold in Europe. The amount of diesel is computed in order to ensure the same mechanical energy delivered by tractors in the reference scenario.

The inventory data are used to build up simapro simulations for each of these scenarios. The LCA methodology is Eco-indicator 99, i.e. a damage-oriented method for life cycle impact assessment. In LCA, emissions are given in mass of pollutant. The amount of pollutant is then converted into an effect in the midpoint methodologies. These effects and assessments are studied impact per impact, each impact corresponding to one environmental problem. The effects are then converted into damage in so-called endpoint methodologies. The point is a common unit used to quantify the damage score. The global score is obtained by summing all the damage scores. The point is therefore the unit used throughout this paper for LCA results. The results are presented below, starting with the energy balance and the LCA energy indicators. Energy indicators are an impact commonly included in LCA. The carbon balance, detailed in the following section, is another impact related to climate change. The other main impacts are described in the last section.

3.2. Energy analysis

In all the scenarios, the methanisation plant produces 116 tons of methane per year, i.e. 5800 MJ/year. The amount of biogas fuel

Table 3
Annual pollutant emissions corresponding to biogas production and use in a dual fuel engine (kg/year).

Emission	Process (kg/year)				
	Transportation	Boiler	Flare	Purification	Burning in dual fuel engine
CO_2	2792	47,981	58,771	70,114	145,300
CO	4.3	40	68.4	–	1726
NO	32	35.37	52.47	0.52	621
NO_2	3.56	3.94	5.84	0.06	69
SO_x	0.09	115	1095	3.5	86
NMVOC	1.9	8	13.7	–	–
CH_4	–	1.12	2244.6	2500	–
HC	–	–	–	–	66
PM_{10}	–	–	–	0.05	–
$PM_{2.5}$	–	–	–	0.139	–
$PM_{2.5<x<10}$	–	–	–	0.0075	–
Diesel soot	0.33	–	–	–	7
Nickel	–	–	–	0.001	–
Zinc	–	–	–	2.338	–

Table 4
Annual energy balance and energy indicators according to different scenarios of biogas production (MJ/year).

	Scenario			
	(1) Ref	(3) Local elec	(4) Without flare	(5) Diesel
Biogas				
Potential	7515	7515	7515	–
Really produced	5800	5800	5800	–
Digester supply (heat + electricity)	682	3881	3881	–
Waste energy (losses + flare)	696	696	116	–
Available for use (methane)	4422	1223	1803	–
Diesel (primary)				
Waste transport	21	21	21	–
Diesel for use	926	256	378	5528
Total	1102	323	464	6427
Electricity (primary)	2702	0	0	0
Charcoal	153	153	173	0
Energy balance				
Biogas energy P_{prod}	5800	5800	5800	–
Other than biogas P_{add}	3957	476	637	6427
Mechanical energy P_{use}	1284	355	523	1284
Efficiency (%)				
η	0.131	0.058	0.083	0.20
LCIA Energy indicator				
Fossil fuel depletion (mPt)	0.29	0.263	0.261	1.51
Cumulative energy demand (mPt)	3.43	1.22	1.18	4.82
$COP^{-1} = P_{add}/P_{use}$	3.08	1.34	1.22	–
$\eta^{-1} = (P_{prod} + P_{add})/P_{use}$	7.48	17.25	11.97	5.01

varies, however, depending on the scenario used for biogas production. This appears clearly in Table 4, where energy balances are detailed for each scenario. For energy, the “French elec” case is exactly the same as the reference case, and is therefore not shown in the table. In the “Biogas ref” scenario, the amount of energy for use is about 4400 MJ/year. This amount is reduced when a substantial part of the methane is dedicated to local electricity production. In this case, the methane for use drops to 1124 MJ/year. Diesel input in the biogas scenario varies in the same proportion as methane energy for use, since the substitution ratio was kept constant. A high amount of diesel is required in our system because of the dual fuel engine. Therefore, the diesel for use is the main component of the diesel input. The proportion of diesel fuel used for waste transport is negligible due the high ratio of local farm effluents, which require no transport. Here, our biogas analysis differs considerably from previous biogas studies, in which the diesel cost comes mainly from waste transport to large digester units. Charcoal energy for purification represents an intermediate amount of incoming energy.

Energy is then split into three categories corresponding to biogas energy at the digester output P_{prod}, energy produced outside the system (P_{add}), i.e. electricity, diesel, charcoal..., and the real mechanical energy delivered by tractors P_{use}. This third category is the one used to divide emissions and other material entries in order to express results with our functional unit. P_{use} is the output energy of the system. Note that the amount of mechanical energy P_{use} is 3.5 times lower in the worst biogas scenario compared to the best. The incoming energy in the system is the sum of P_{add} and P_{prod}. Neglecting renewable energy use for electricity production (less than 20% in France), we consider that both electricity from outside and diesel fuel are the non renewable energies of our system. They are roughly equal to P_{add}. Then, the energy efficiency of our fuelling system is given by:

$$\eta = \frac{P_{use}}{P_{prod} + P_{add}} \quad (3)$$

As the biomass incoming energy P_{prod} is renewable, its energy content is not assessed in the same way as other incoming energies. It was therefore considered convenient to introduce the coefficient of performance of our system, that is given by:

$$COP = \frac{P_{use}}{P_{add}} \quad (4)$$

As shown in Table 4, the best efficiency η is obtained for the diesel scenario, as the energy needs for production and transportation are very low for this fuel. The best score for biogas fuel is obviously observed when most of the biogas is dedicated to use. η is below 10% if part of the biogas is used to produce electricity for the system. This part reduces P_{use}, as well as P_{add}, leading to a non-linear effect on the efficiency.

Two indicators related to energy analysis in LCA were extracted from the simapro results, namely fossil fuel depletion and cumulative energy demand. Fossil fuel depletion, (noted hereafter FFD) expresses a damage to resources, as the surplus energy needed for future extractions of fossil fuels in the Ecoindicator99 method. The cumulative energy demand (noted CED) was defined to represent the direct and indirect use of energy throughout the life cycle [9]. It is mainly based on the primary energy requirements and is an indicator that is well correlated with most of the Eco-indicator 99 indicators (global warming, fossil fuel depletion, acidification, eutrophisation and photochemical ozone formation). Huijbregts et al. therefore argue that it could be used in association with land use as an ecological footprint indicator. Both indicators are given for damage analysis and are therefore expressed in points.

The final step in the LCA approach is to use the functional unit to dimension impacts and compare scenarios. All the results are therefore divided by P_{use}, in order to determine what is emitted per unit of energy output. This is the reverse of the efficiency definition in which the ratio quantifies the energy output per unit of energy input. Consequently, the two LCA indicators FFD and CED are very different from the energy efficiency results (η). In LCA, the end product, i.e. here the mechanical energy output P_{use}, is used as the denominator whereas the energy input is the numerator. LCA indicators could be interpreted as the inverse of efficiency. This is not exactly the case, however, as can be seen more clearly in Fig. 2.

For FFD, the best score, i.e. the smallest FFD value, is obtained for the less efficient systems of biogas production: “local elec” and “without flare”. But the FFD indicator is not very sensitive to the

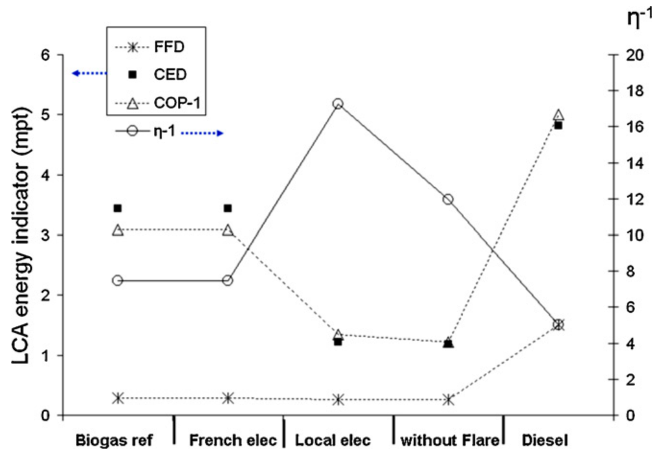

Fig. 2. Comparison between traditional efficiency indicators and LCA energy indicators for different biogas scenarios and diesel used in agricultural vehicles.

production scenario: the maximum gap between scenarios is about 87% whereas energy outputs vary with a factor of 3.3. Comparing fuels, biogas fuel obviously has a lower impact on FFD than diesel fuel: the "reference" biogas fuel score is about 6.6 times lower than that of "diesel" fuel. This is roughly the difference in the diesel consumption between the "biogas ref" and "diesel" scenarios for the same P_{use}. In fact, FFD is approximatively the diesel consumption per unit of agricultural work.

The CED indicator is more sensitive to scenarios, being 3 times higher in the worst scenario than in the best one. It is also less penalising for diesel. The CED corresponds approximatively to the outside energy per unit of agricultural work. It shows clearly that the P_{prod} values were not properly taken into account in our LCA approach. Neglecting P_{prod}, the LCA energy indicators behave like a coefficient of performance of the system. It varies in exactly the opposite way to the real efficiency computed from a traditional energy balance.

This point illustrates the difficulty in applying the LCA methodology to a biofuel production process. In many of the LCAs proposed for biofuels [17,20], the incoming energy does not include the energy content of the organic material input. An easy environmental optimisation of the process is then obtained by replacing the incoming energy by the energy produced by the process itself. That is in fact what we did with our scenarios. This yields a green output energy but it does not properly reflect the decrease in the available amount of output energy. Our case is particularly sensitive to this distorsion because P_{add} is very high compared to P_{prod} in our system.

3.3. Carbon balance

Carbon balance is a methodology developed by ADEME [21] that calculates the greenhouse gas emissions (in equivalent tons of C or CO_2) of a given industrial activity. It applies to all activities that emit CO_2, whether they are manufacturing, transformation or service industries. This methodology is compatible with the ISO 14064 standard, the GHG Protocol and the 2003/87/EC Directive that established a scheme for greenhouse gas emission allowance trading.

During the carbon balance study, the different sources of emissions are examined and measured over the complete production cycle: the initial manufacture of materials entering the system, transformations undertaken (consumption of raw materials, fossil fuels, electricity, etc.), transport (upstream and downstream), transport of persons and waste treatment. Carbon Balance is a tool that provides content for GHG environmental policy management in the same spirit as LCA, but it focuses more on climate change and energy dependency. The calculation rules for carbon balance are similar to those for greenhouse emission saving in the 2009/28/EC Directive. The carbon balance is hence important because vehicles are now required to reduce their CO_2 footprint. Besides, the dual fuel engine enables a 20% reduction in CO_2 emissions compared to a diesel engine. The reduction is above 80% if the biogenic nature of biogas is considered. This CO_2 saving at the end-use stage is however totally cancelled out by CO_2 emissions occurring during biogas production (boiler, electricity) and by the methane losses during production. From a motorist's point of view, the dual fuel tractor is a low CO_2 emitter compared to the diesel version, but things are different when the whole life of power supply for vehicles is considered, as is done in the following.

Table 5 gives all the greenhouse gas emissions that have to be taken into account in the carbon balance, i.e. CO_2, CH_4 and NO_2. As digestate spreading is outside our system boundary, the NO_2 contribution is of minor importance in our process and was therefore not taken into account in the balance. Additional data used in the carbon balance were: the diesel part in CO_2 for use is 69 g CO_2/kWh, French electricity is assumed to produce 180 g CO_2/kWh, and the global warming potential of CH_4 is 23 (time horizon 100 years).

The first column summarises the GHG emissions: biogas produces 455 tons $CO_{2,eq}$/year and the surrounding production process generates 227 tons $CO_{2,eq}$/year more, related to fossil carbon combustion. By this method of computation, biogas, with 531 g $CO_{2,eq}$/MJ, produces more CO_2 than diesel, with 324 g $CO_{2,eq}$/MJ. GHG emissions per unit of agricultural work increase for other scenarios: although real emissions remain constant, the available energy for use decreases and is disadvantageous to these other scenarios.

However, the 2009/28/EC Directive and the carbon balance methodology specify that emissions from the fuel in use shall be taken to be zero for biofuels. We extended this assumption to the other subprocesses using biogas fuel: boiler, flare, and electricity engine. Therefore, all the biogenic methane combustion has zero GHG emissions. Biogenic CO_2 arising from the CO_2 content of raw biogas was also set to zero, due to its biogenic nature. In the end, only fossil CO_2 and methane losses were taken into account in the proper carbon balance: 215 g $CO_{2,eq}$/MJ is therefore the correct carbon balance of biogas and it is below the diesel value. The CO_2 saving is the difference in GHG emissions between conventional diesel fuel and biogas: this saving is about 33% including the end-use stage.

Looking at the other scenarios, biogas emits less $CO_{2,eq}$ than diesel. In the local elec scenario, global $CO_{2,eq}$ emissions are reduced but the energy available for use also decreases at a higher rate. This explains why the g $CO_{2,eq}$/MJ ratio is higher (257 observed for this case). CO_2 savings are lower than those stipulated by the directive (80% for biogas) in all simulations. This may be due to the allocation choice made in the directive between biogas and digestate. Indeed, if 100% of the avoided methane is allocated to biogas, GHG emissions become negative: negative values represent in fact a benefit for the environment. Then, from Table 5, biogas fuel presents a beneficial effect on climate change if the allocation choice is modified. Care must be taken, however, in comparing scenarios with negative values. $CO_{2,eq}$ emissions drop to −2160 g $CO_{2,eq}$/MJ in the local elec scenario. Here, the GHG saving is the highest when the available energy for use is the smallest. The interpretation of negative values is therefore not straightforward because the worst system, i.e. the least efficient one, appears to be the best in the carbon balance approach. Moreover, whatever the scenario, it is shown here that biogas is an alternative to diesel that has an interesting impact on climate change when either the biogenic nature of carbon or avoided methane emissions are taken into account.

Table 5
Annual carbon balance of biogas fuel and diesel fuel path.

	(1) Biogas Ref	(2) French elec	(3) Local elec	(4) Without flare	(5) Diesel
Fossil CO_2 (T $CO_{2,eq}$/year) [a]	227	227	43	55	416
Biogenic CO_2 in raw biogas	87				–
Biogenic CO_2 from methane combustion	319				–
CH_4 losses[b] in T $CO_{2,eq}$/year	49				–
CH_4 avoided[b] in T $CO_{2,eq}$/year	−1384				–
Mechanical energy (GJ)	1284	1284	355	523	1284
Total g $CO_{2,eq}$/MJ[c]	531	531	1400	972	324
Total g $CO_{2,eq}$/MJ[c] fossil and methane losses	215	215	257	197	324
Total g $CO_{2,eq}$/MJ[c] with avoided methane	–	−454	−2160	−1443	324

[a] Fossil CO_2: it includes all the CO_2 emitted during the combustion of the charcoal, the diesel used for the transport of waste, the diesel for the use of tractors and also that corresponding to the production of the primary "outside" electricity.
[b] Methane emissions: these emissions are about 2.32 tons of CH_4 losses during production and −60.2 tons of CH_4 avoided by waste digestion in some scenarios. Avoided emissions are negative because they are substracted.
[c] MJ: refers here to our functional unit MJ of agricultural work, instead of the low heating value of fuel in the directive.

3.4. Environmental impacts of biogas fuel

Energy is not the only key for environmental impacts: the global environmental assessment is determined using the Ecoindicator99 method developed by Goodkoep [22]. Fig. 3 shows the global impact assessment for all the scenarios. It takes into account all types of pollutant emissions. The impact on 'fossil fuel depletion' (FFD) was excluded from these results: FFD is in fact the most important impact for mobile applications and FFD scores were so high that other impacts appeared negligible by comparison in the analysis. Most of the details about FFD were therefore given separately in the section on energy balance. All the impacts have the same weight and all the results are expressed in points, the standard unit of end-point assessment. The first point to notice is that impacts show the same overall profile for biogas and diesel: most of the environmental impacts are linked, in decreasing order, to 'Respiratory inorganics', then "climate change", "acidification/eutrophisation" and "ecotoxicity". These impacts account for over 92% of the final score.

For the "Respiratory disease and inorganics" (RDAIS), the dual fuel tractor again presents a higher single score than the diesel tractor. The electricity used for compression of the biogas and for mixing/pumping digestates makes quite an important contribution. This is revealed by comparing the "French elec" and the "European elec" scenarios. In fact, it is known that most of French electricity comes from nuclear production plants: using this electricity therefore produces a higher radiation score, but has less impact on climate change, carcinogens and respiratory organics

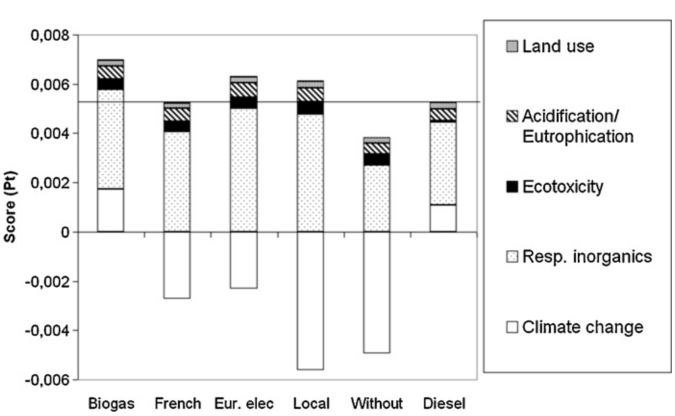

Fig. 3. Environmental single score of biogas and diesel fuel using Eco-indicator99 method.

than does the electricity produced from coal and oil. In the "Local elec" scenario, it can be seen that the environmental score of biogas is enhanced compared to electricity coming from the European mix. This enhancement is not sufficient however to be interesting in the French context. Another substantial part of the score is linked to flare combustion, as can be seen in both the "Local elec" and "Without flare" scenarios. The "Without flare" scenario is the only scenario in which biogas can be demonstrated to be more environmentally beneficial than diesel. This result is mainly attributable to the highly significant decrease in the score of the "Without flare" scenario.

For "climate change", the balance also disfavours methane production. This result, however, which is again due to the high contribution of the combustion process, should be treated with caution as it basically depends on the allocation choice for avoided methane emissions. If all the avoided methane emissions are allocated to biogas production, biogas then has a positive impact on climate change: this is shown by the negative score of "climate change" in the "French elec" scenario compared to the "Biogas ref" one. Results are similar to carbon balance results and explanations were given in the carbon balance section above.

Acidification and eutrophisation are environmental problems mainly linked with SO_x, NO_x and hydrocarbon compounds including methane. The differences between the various biogas scenarios are rather small: the lowest score is observed for biogas "Without flare": the decrease in the acidification score comes from the transfer of biogas in flares to biogas in engines. In engine exhausts, NO_x are much lower than in flares due to the depollution system. The reduction is so great that it has a noticeable effect on the acidification score.

The effect on ecotoxicity, which is much greater for biogas than for diesel, is mainly connected to the sulphur emissions: for biogas cases, agricultural waste contains a high quantity of sulphur, higher than that of municipal organic waste or waste from the food industry. Gaseous sulphur emissions occur during anaerobic digestion. These emissions are released into the exhaust of the boiler, flare and during the burning of purification filters. The impact of the sulphur emissions increases the ecotoxicity indicator, irrespective of the scenario, because all the sulphur contents in the waste are released into the atmosphere after combustion, whether for the flare or for the activated charcoal.

The total impact of biogas fuel is higher in the "biogas ref" scenario than that of diesel fuel in the "diesel" scenario. Taking avoided methane emissions into account, biogas fuel is beneficial for the environment by reducing the climate change effect of engine use. Diesel and biogas fuels have nearly the same environmental score:

the variability in the biogas score is clearly related to electricity production. Lastly, eliminating the flare is one way to obtain methane that has the smallest impact on the environment. Its global score is below that of diesel.

4. Conclusion

This paper has presented an analysis of the environmental impact and the energy interest of anaerobic digestion to produce biogas fuel. It is based on a typical digester of agricultural waste having the same characteristics as existing agricultural methanisation units in France. The pollutant emissions and the associated energy needs were estimated for several methane production scenarios with a view to its use in tractors equipped with tier 3b engines, i.e. the current standard for pollutant emissions in the exhaust.

An energy analysis was undertaken by making a complete balance of the energy input and output, including the biomass content. This analysis shows that LCA indicators relative to energy focus on the renewable nature of the fuel rather than on its energy performance. Using these indicators, the optimisation of biofuel production lies in consuming the biogas itself to cover the needs of the cultivation, manufacturing, and transport phases. It shows the interest of using farm tractors working with high substitution rates of biofuel instead of diesel. With a traditional LCA approach, this suggestion should lead to decreasing the fossil fuel depletion of all biofuels produced from agricultural waste. However, this approach decreases the amounts of biofuel produced. This decrease in production is not apparent in the current LCA energy indicators.

The carbon balance analysis conducted here shows that biogas fuel requires a lot of energy, mainly during the combustion process: the amount of CO_2 emitted during production is therefore high. But when one considers that anaerobic digestion reduces methane emissions from waste, and that the CO_2 comes from biogenic sources, it is then possible to achieve biogas fuel produced with very low CO_2. Using methane instead of diesel in engines leads to a 20% saving in CO_2 at the end-use stage. However, the biogenic carbon assumption or avoided methane emissions mean that a considerable CO_2 saving can be made in the biogas LCA. This saving is huge compared to the end-use savings. It is therefore somewhat irrelevant to assume that "dual fuel" vehicles are low carbon emitters by looking only at the end-use balance.

The study of the environmental issues of biogas production has shown that the main environmental problems relative to biogas fuelled tractors are rather similar to those of a diesel tractor. It is possible to bring the environmental score of biogas fuel below that of diesel by working on the management of the flare and using the local production of electricity. Then, the allocation of the methane avoided by anaerobic digestion remains the determining factor in assessing the global environmental impact of biogas biofuel.

Lastly, biogas fuel has a poor energy efficiency and requires a considerable amount of energy for compression and fuel purification. As for some other biofuels, the net energy ratio of biogas is therefore low. Because of this poor energy efficiency, it thus seems difficult, from an energy point of view, to promote biogas fuel, especially when compared to diesel fuel. This is all the more difficult as the production potential for small methanisation plants is low. Apart from considerations of energy efficiency, however, biogas plants have a low global environmental impact. That is why they are an interesting alternative for energy paths such as local electricity production. Further work should therefore be done to study the monthly production of digesters and to try and replace flares with biogas purifiers in order to obtain the small amount of biofuel required to spread digestates.

Acknowledgment

The authors would like to thank Fabrice Belline for his help, advice and comments. His explanations on the methanisation process were an important contribution to this work.

References

[1] Chang J, Fontenelle J, Serveau N. Inventaires des émissions polluantes atmosphériques en France, séries sectorielles et analyses et étendues, Tech. rep., CITEPA, Paris; février 2007.
[2] Couturier C, Bochu J, Pointereau P, Doublet S. Plan Climat 2003, Groupe Agriculture, Forêts, Produits dérivés, 12 propositions pour lutter contre le changement climatique dans le secteur de l'agriculture, Tech. rep., Solagro; Septembre 2003.
[3] Lenzen M. Current state of development of electricity generating technologies: a literature review. Energies 2010;3:462–591.
[4] Hartmann JK. Life-cycle-assessment of industrial scale biogas plants, Tech. rep., Fakultät für Agrarwissenschaften, Georg-August-Universität, Göttingen; 2006.
[5] Borjesson P, Berglund M. Environmental systems analysis of biogas systems—Part 1: Fuel-cycle emissions. Biomass and Bioenergy 2006;30(5):469–85.
[6] Chevalier M, Meunier F. Environmental assessment of biogas co- or trigeneration units by life cycle analysis methodology. Applied Thermal Engineering 2005;25:3025–41.
[7] Monier E, Wenish S. Analyses du cycle de vie des modes de valorisation énergétique du biogaz issu de méthanisation de la fraction fermentescible des ordures ménagères collectées sélectivement en France, Tech. rep., Ademe; Septembre 2007.
[8] Berglund M, Borjesson P. Assessment of energy performance in the life-cycle of biogas production. Biomass and Bioenergy 2006;30(3): 254–66.
[9] Moras S. Environmental assessment of energy production by combustion of biogas provided by the anaerobic digestion of agricultural biomass. International Journal of Environmental Technology and Management 2008;9(4):413–24.
[10] Poitrat E. Elaboration d'un référentiel méthodologique pour la réalisation d'Analyses de Cycle de Vie appliquées aux biocarburants de première génération en France, Tech. rep., Ademe; Avril 2008.
[11] NF-EN-ISO-14044. In: Environmental management, life cycle assessment: Principles and framework. AFNOR; 2006.
[12] Ademe, Analyses en cycle de vie appliquées aux biocarburants de première génération consommés en France, Tech. rep., Service bioressources; Fevrier 2010.
[13] Samaras Z, Zierock K. Off-road vehicles—a comparison of emissions with those from road transport. Science of the Total Environment 1995;169(1–3):249–55.
[14] Lacour S, Galiégue Y, Vaitilingom G, Pradel M, Gallet P, Guiscafré P. The contribution of field experiments to life cycle assessment of agricultural works: application to spreading works. In: Cemagref, editor. Int. Conference on agricultural engineering, towards environmental technologies. Clermont-Ferrand; 2010.
[15] Kalinci Y, Hepbasli A, Dincer I. Biomass-based hydrogen production: a review and analysis. International Journal of Hydrogen Energy 2009;34:8799–817.
[16] Borel L, Favrat D. Thermodynamique et énergétique: de l'énergie á l'exergie. Lausanne: EPFL-PPUR; 2005.
[17] Martinez J, Guiziou F, Gueutier V. Emissions de méthane au cours du stockage des déjections animales, Tech. rep., Division Production et Economie Agricoles, Rennes; 1995.
[18] Selim MYE. Effect of engine parameters and gaseous fuel type on the cyclic variability of dual fuel engines. Fuel 2005;84(7/8):961–71.
[19] Sahoo B, Sahoo N, Saha U. Effect of engine parameters and type of gaseous fuel on the performance of dual-fuel engines—a critical review. Renewable and Sustainable Energy Reviews 2009;13:1151–84.
[20] Huijbregts M, Rombouts LJA, Hellweg S, Frischknecht R, Hendriks AJ, Meent D, et al. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environmental Science & Technology 2006;40(3):641–8.
[21] Jancovici JM, Bilan Carbone—Guide méthodologique v6.1—Objectifs et principes de comptabilisation, Tech. rep., ADEME; Juin 2010.
[22] Goedkoop M, Spriensma R. The Eco—indicator 99—a damage oriented method for life cycle impact assessment—Methodology Report. 3rd edition PRé - Consultant B.V; 2001. Tech. rep.